MECHANICS.

No. I.

POLARIZING LIGHT.

The SILVER MEDAL *was presented to Mr. J. F.* GODDARD, *of the Polytechnic Institution, Regent Street, for his Apparatus for Experiments on Polarizing Light. The following Communication has been received from Mr. Goddard on the subject.*

THE beautiful phenomena of colours produced by the transmission of polarized light through doubly refracting crystals, the various bands and concentric rings, composed of all the most brilliant and delicate tints of the solar spectrum, and the different forms, changes, and modifications that they may be made to undergo and exhibit, are so numerous and varied, as to furnish a display of the most splendid experiments within the whole range of science; whilst their value and importance in the sciences of mineralogy and chemistry, from the deep insight which polarized light affords of the minute structure and constitution of transparent bodies, which appear, upon every other mode of examination, to be perfectly homogeneous, yet, when viewed in polarized light, exhibit the most exquisite structure (as is seen in the extraordinary configurations of apophyllite, analcine, and many others,

displaying the influence of laws of combination, of which it is impossible, by any other means, to obtain the least knowledge), renders an exhibition of these experiments not only interesting, but most desirable and important. For this purpose, after having tried numerous experiments upon the different methods now in use, I have constructed a polariscope, adapted to Mr. Cary's hydro-oxygen microscope, which is capable of exhibiting, upon a disc, on a highly magnified scale, all the beautiful and curious phenomena of this interesting branch of science.

But, previous to describing the polarizing apparatus, and the effects that may be produced by means of it, it may be as well to give a short and popular explanation of what polarized light is; and, to do this, we must notice the principal hypothesis upon which the Huygenian or undulatory theory of light is founded, at least so far as relates to the phenomena under consideration: but in so doing, I beg that I may not be understood as advocating this theory in opposition to any other, but merely using it as affording a popular explanation, which those who give a preference to its rival will have no difficulty in understanding, and can, if they please, substitute the language of its rival, the corpuscular theory.

The following are the principal postulata, according to Sir W. J. Herschel, upon which this, the undulatory theory, is founded.

1. It is supposed that a rare, elastic, and imponderable medium, or ether, fills all space, and pervades all material bodies, occupying the intervals between their molecules, and possessing inertia, but not gravity.

2. That the molecules of ether are susceptible of being set in motion by the motions of the particles of ponderable matter, which motion it communicates in a similar

manner to adjacent molecules; thus propagating it, in all directions, according to the same mechanical laws which regulate the propagation of undulations in other elastic media, as air and water, according to their respective constitutions.

3. That vibrations communicated to the ether, in free space, are propagated, through refractive media, by means of the ether in their interior, but with a velocity decreasing with its inferior degree of elasticity.

4. That when regular vibratory motions, of a proper kind, are propagated through the ethereal media, and pass into our eyes, and reach and agitate the nerves of the retina, they produce in us the sensation of light, in a manner more or less analogous to that in which the vibrations of the air affect our auditory nerves in producing sound.

5. That as, in sound, the frequency of the aerial vibrations, or number of excursions of each molecule of air, determines the note, so, in light, the frequency of the vibrations made on our nerves, in a given time, by the ethereal molecule, determines the colour of the light: and that, as the extent of the vibrations of air determines the loudness of the sound, so the extent of the vibrations of the ethereal molecule determines the intensity of light.

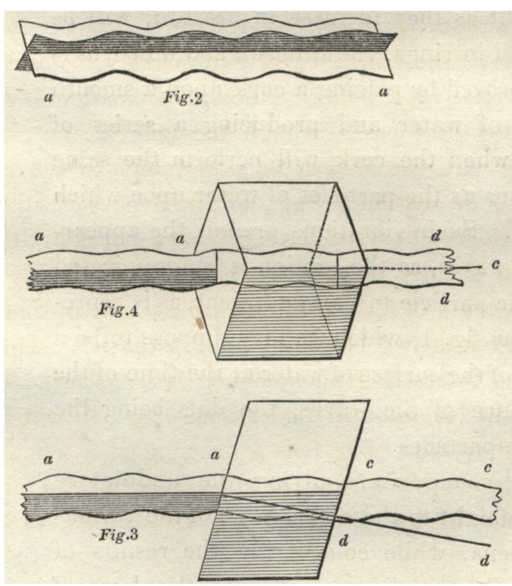
To understand how waves are produced, by the vibrations of the particles of an elastic medium, we have only to study the waves produced upon the surface of a pond of water, when rain is falling; it will be found that the particles of water driven down by a single drop of rain force the adjacent ones upwards, the air above, in consequence of its being more elastic, yielding sooner to the pressure exerted by the displaced particles on those surrounding the point of disturbance. Thus a wave is raised

round this point by the momentum of the falling drop, and, as soon as such momentum is spent, the effect of gravity draws the raised particles down to the common surface of the liquid; the momentum, however, which they have acquired in this descent, carries them below the level, or point of rest; and, in descending below this point, they cause, among the adjacent particles of still water, a motion similar to that by which they were themselves first actuated by the falling drop. The second wave thus produced will, in its descent, cause a third; and thus a series of waves, decreasing in height as they increase in breadth, will be produced in rings, vibrating up and down, as is easily proved by placing a cork upon a smooth surface of water and producing a series of waves, when the cork will perform the same vibrations as the particles of water upon which it floats. Such vibrations present the appearance of waves, as the motion is communicated from one particle to those adjacent, as is represented by fig. 1, which we may suppose to be a section of the surface of water at the time of the appearance of the waves, the dots being the separate particles.

Fig.1

Dr. Young, in applying the undulatory theory of light to the explanation of the various phenomena, while considering the results of Sir D. Brewster's researches on the laws of double refraction, first proposed the hypothesis of transversal vibrations, which has since been shewn to be a necessary consequence of

dynamical principles, and is most important to the explanation of our subject. These vibrations he illustrated by the propagation of undulations along a stretched cord, agitated at one end, which, supposing a person to hold in his hand, and, by moving first quickly up and down, a wave will be produced, which will run along the cord to the other end; and then, by a similar movement, but from the right side to the left, another wave will be produced, which will run along the cord as the former; but the vibrations or undulations of each will be in planes at right angles to each other and independent of each other, one being in a perpendicular plane and the other in a horizontal plane; so that, according to this theory, fig. 2



may be supposed to represent a ray of ordinary or unpolarized light. I have chosen this representation of a single ray of ordinary light, which is a drawing of one of

Mr. Woodward's beautifully simple card models,* as it conveys at once to the mind a distinct notion of the planes in which the vibrations take place. A beam of light we may, therefore, conceive to consist of a succession of systems of waves following each other with immense rapidity, and comprising an immense number of rays, the vibrations of which are performed in every possible plane.

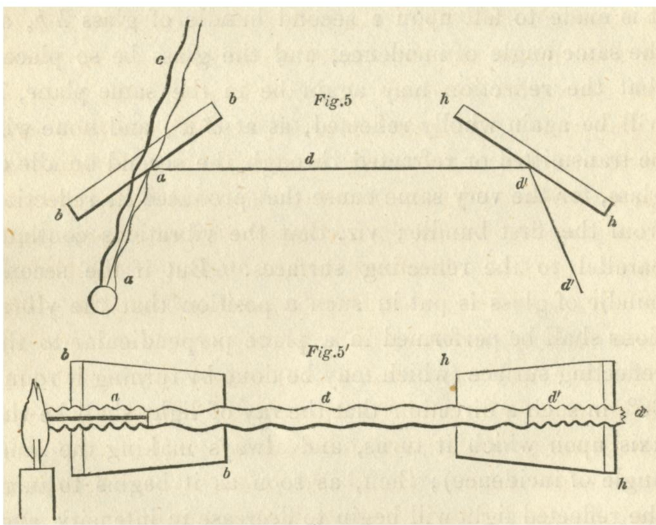
In the transmission of ordinary light through transparent or refracting bodies, perfectly homogeneous in their structure, and of a uniform temperature throughout, such as pure water, well annealed glass, and many kinds of crystallized bodies, as alum, common salt, Fluor spar, &c., a single beam will be refracted singly; and if we make a pin-hole in a card, and place it behind one of these bodies, and behind the card a candle, so that the light may first pass through the hole in the card, and then through the subject of experiment to the eye, the hole will be distinctly seen, and will be perfectly single. But in the most crystalline substances this is not the case, for such usually possess the property of double refractions, a beam of light passing through any of them being refracted into two beams of equal intensity. This beautiful and interesting phenomenon is seen, in an eminent degree, in Iceland spar (calcareous spar), in which it was first discovered. Fig. 3 is a drawing of a model representing a rhomb, with a ray of ordinary light *a a* incident upon one of its natural faces, and which, in passing

* This is hardly a sufficient acknowledgment of the merit due to a gentleman, whose extensive knowledge, and love of science, are only surpassed by his private worth and excellence: the merit of any other application that may be made of them is unquestionably due to the mind that originally suggested them.

through the crystal, is divided into two rays, one of which, *c c*, being refracted according to the ordinary laws of refraction, is called the ordinary ray; the other, *d d*, not obeying the same law, but being refracted in an extraordinary manner, is called the extraordinary ray. Fig. 4 is another view of the same model. Now, on analysing these rays, either with a second rhomb, or otherwise, which will be better understood as we proceed, they are found to be precisely alike in every respect, of the same character, and possessing the same properties, but that these properties and characters are at right angles to each other; the doubly refracting action of the crystal upon light consisting in the separation of the two sets of undulations, or transversal vibrations, of which a ray of ordinary light consists; the vibrations of the ethereal molecule, in the ordinary ray, will be in one plane; while the vibrations of the ethereal molecules, in the extraordinary ray, will be in another plane, at right angles to it, as represented by fig. 3; and, if we suppose this to be a bird's-eye view, the vibrations of *c c* will be in a horizontal plane, and the vibrations of *d d* in a perpendicular plane; each of which is said to be polarized light: hence, when the question is asked, what is the difference between common and polarized light? the reply, according to the undulatory theory, is, that a ray of ordinary or common light, whether artificial or solar, consists of two sets of undulations or vibrations of the molecules of the ethereal or imponderable medium, which we have supposed to fill all space; and that these two sets of undulations are performed in planes, at right angles to each other, as represented by fig. 2; but that polarized light consists of one set of undulations, or vibrations, performed in one plane. The polarization of light, then, is simply

the separation of the two sets of undulations, or vibrations, of which ordinary light is composed, and thus producing a beam of light in which the vibrations of the ethereal molecules are all in one plane.

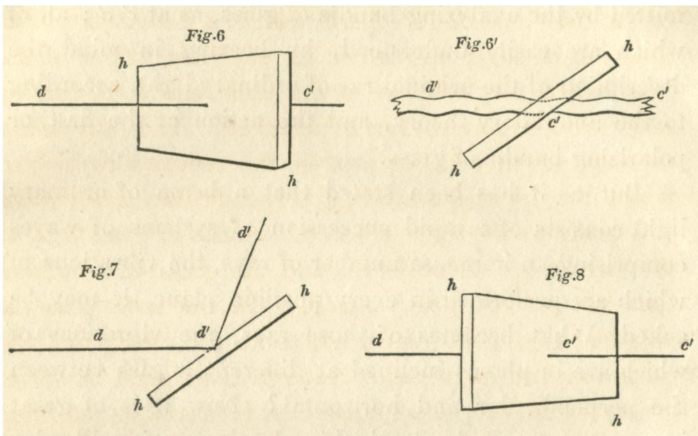
Now, this separation, or polarization (as it has rather improperly been called), may be effected with common crown glass, either by ordinary reflection or refraction, each of which will exhibit the same effects. In order to understand this, let *b b*, fig. 5, represent a bundle of



plates of common glass, placed so that a ray of ordinary light *a a* may form an angle of incidence of 56° 45′ with a line perpendicular to their surface; then the light reflected, and represented as passing off at *d*, will be polarized light; and if a proper number of plates, which, for the same angle of incidence, is 27, be employed, the light transmitted at *c* will be polarized also, the two rays possessing the same properties, but at right angles to each other. Thus, in the reflected ray, *d*, the

vibrations are supposed to take place in a perpendicular plane, this being a bird's-eye view (fig. 5′ being a horizontal view of the same thing), whilst, in the refracted ray, *c*, the vibrations are performed in a horizontal plane. This will be easily understood on analyzing either of the rays, which may be done by the same means as that by which the original beam is polarized. Thus, supposing we experiment with, or analyse the reflected ray, *d*, in which the vibrations are in a perpendicular plane, when it is made to fall upon a second bundle of glass *h h*, at the same angle of incidence, and the glass be so placed that the reflection may again be in the same plane, it will be again wholly reflected, as at *d′ d′*, and none will be transmitted or refracted through the second bundle of glass, for the very same cause that produced its reflection from the first bundle; viz. that the vibrations continue parallel to the reflecting surfaces. But if the second bundle of glass is put in such a position that the vibrations shall be performed in a plane perpendicular to the reflecting surface (which may be done by turning it round 90°, in such a direction that the ray of light shall be the axis upon which it turns, and always making the same angle of incidence); then, as soon as it begins to turn, the reflected light will begin to decrease in intensity, and, as it decreases, a portion will begin to be transmitted or refracted through the glass, which will increase in the same ratio as the reflected light decreases; and when the bundle of glass has turned 90°, in which position we see it represented at the bird's-eye view, fig. 6, and at the horizontal view, fig. 6′, the light *d* is wholly transmitted or refracted, as at *c′ c′*, no portion being reflected. In such a position, the vibrations will be in a plane perpendicular to the reflecting surface; and such vibrations are

always transmitted, and not reflected, as we also see has taken place in the polarization of the original beam of common light (*a*, fig. 5) before referred to. Now, let the



second bundle of glass *h h* continue to turn, it will be seen that, as soon as it begins to move, the transmitted light *c' c'* will begin to decrease, a portion beginning to be again reflected, which, as the glass turns, will increase in intensity, in the same ratio as the transmitted light decreases, until it has turned another 90°, or reached 180° from the first position, as seen at fig. 7, where the plane of reflection is again parallel to the plane in which the vibrations take place; consequently, the whole light is again reflected at *d' d'*, none being transmitted, for the same reason as before stated. On continuing the revolution, the same thing occurs at each quadrant of a circle. In fig. 8, the bundle of glass *h h* is represented as having turned 270°, or $\frac{3}{4}$ of a circle. In which position the same thing occurs as at 90°, where the light *d* is wholly refracted or transmitted through the glass, as at *c' c'*; so that it is evident, in these experiments, that there are two

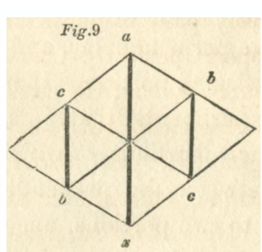
positions, shewn in figs. 5 and 7, in which the same ray of polarised light *d* is wholly reflected, as at *d′ d′*, and two other positions, figs. 6 and 8, in which it is wholly transmitted by the analyzing bundle of glass, as at *c′ c′*; all of which are easily understood, by bearing in mind the description of the original ray of ordinary light, according to the undulatory theory, and the action of the first, or polarizing bundle of glass.

But, as it has been stated that a beam of ordinary light consists of a rapid succession of systems of waves comprising an immense number of rays, the vibrations of which are performed in every possible plane, it may be asked, What becomes of those rays, the vibrations of which are in planes inclined at different angles between the perpendicular and horizontal? Now it is of great importance to understand this clearly, as it will also enable us to understand how all the various and beautiful phenomena of colours are produced. The experiments however which we have been noticing with the analysing bundle of glass, will assist us in this; for, if we refer again to fig. 5, we find that the vibrations of the polarized light *d* are represented as being performed in a perpendicular plane, and that the second bundle of glass *h h* is so placed that such vibrations are parallel to its plane of reflection, and that, consequently, in such a position the light is again reflected, for the reasons there stated. Now, if we mark well what follows, when the second bundle of glass is made to turn round, we shall understand what becomes of those vibrations which are inclined at different angles, between the perpendicular and horizontal: for when the second bundle of glass begins to turn, its plane of reflection will begin to form different angles with the perpendicular and horizontal, and as soon

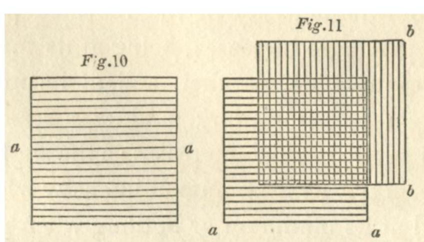
as it begins to move, a portion of the reflected light begins to be transmitted, which, as it turns, increases in intensity; and when it has reached 45°, the light *d* is divided into two equal portions, one of which is reflected, and the other refracted or transmitted through the second bundle of glass, in each of which the vibrations are inclined 45° to the perpendicular, but at right angles to each other. Thus, in the reflected portion, the vibrations will be parallel to the plane of reflection, which is now inclined 45° to the perpendicular; but, in the transmitted portion, the vibrations will be in a plane perpendicular to the plane of reflection, and of course inclined 45° on the opposite side of the perpendicular, and consequently at right angles to the reflected portion. It will be understood, then, from these experiments, that, in a beam of ordinary light, those rays, the vibrations of which are inclined at different angles between the perpendicular and horizontal, are divided into two portions, one of which is reflected, and the other refracted or transmitted, the vibrations in each of which are at right angles to each other; but in neither are they in the same plane as in the original ray, the reflected portion being parallel to the plane of reflection, and the refracted portion being at right angles or perpendicular to the reflected portion; and consequently, whatever angle the plane of reflection makes with the plane of vibrations of the original ray, the vibrations of the reflected portion will make the same angle, being always parallel. But the intensity of the reflected portion will decrease as the angle increases, being at its maximum or greatest intensity when parallel, and at its minimum or nothing when perpendicular; and *vice versâ* with the transmitted portion, which increases as the angle increases up to 90°, being at its maximum of intensity when perpendicular, and at its minimum or nothing when parallel.

Amongst crystallized minerals, there are many possessing the property of polarizing the light transmitted through them; the most remarkable of which, however, is the tourmaline, which, from the mistaken importance and value that has been attached to it, we must briefly notice.

This mineral crystallizes in long prisms, whose primitive form is the obtuse rhomboid, having the axis parallel to the axis of the prism. It must be remembered, also, that the axis of crystals is not like the axis of the earth, a single line within the crystal, but a single direction through the crystal: for supposing fig. 9 to represent a crystal of any kind, the axis of which is in the direction $a x$, if we divide such a crystal into four, along the lines $b b$ and $c c$, each separately will have its axis $a o$, $o x$, $c b$, and $b c$, which, when united in one crystal, are all parallel: every line, then, within the crystal parallel to $a x$, is an axis.



Now, if we cut a crystal of tourmaline of a proper kind, parallel to the axis, into thin plates of a uniform thickness (about one-twentieth of an inch), and polish each side, it possesses the property of polarizing the light transmitted through it in a remarkable manner. Fig. 10 represents one of these plates, the lines across which we may suppose to be parallel to the axis. Now, if we hold



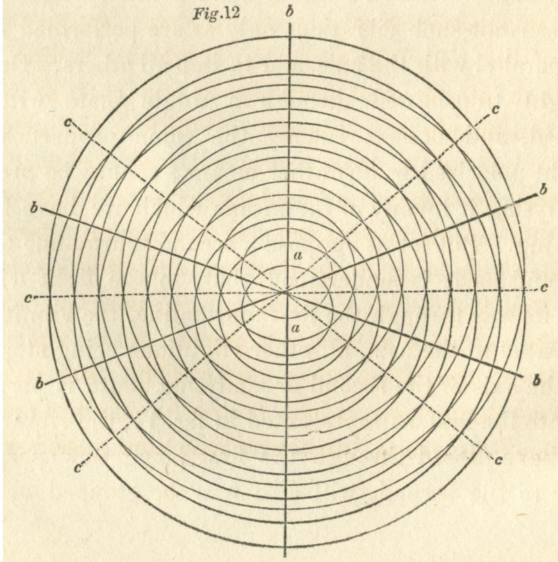
such a plate before the eye, and look at the light of the sun or flame of a candle, or any artificial light, a great portion will be transmitted through the plate which will appear quite transparent, having only the accidental colour of the crystal, which, in specimens suited for these experiments, is generally brown or green; but the light so transmitted will be polarized light, and on being analysed by a second plate, which may be done by looking through both at the same time, we shall find that when the axes of both plates coincide, *i.e.* are parallel to each other, the light which has passed through the first will also freely pass through the second, and they will together appear perfectly transparent; but when one is turned round, so that the axes of each plate are at right angles (across each other) as represented in fig. 11, not a ray of light will pass through, — they will appear perfectly opaque, although we may be looking at the meridian sun.

Now if we suppose the structure of the crystal to be represented by a grating, the bars of which are the axis, we may conceive that its action upon ordinary light will be to transmit such vibrations only as are performed in a plane parallel with the axis, and to stop all others. Hence the light transmitted through a single plate will be polarized, and possess exactly the same properties as the light polarized by any other means; as may be proved by analysing it by any of the means which we have been describing. But let us suppose a second tourmaline to be used; and as it is understood that, in the light which makes its way through the first tourmaline, the vibrations are parallel to the axis, all other vibrations being stopped when the axis of the second or analysing plate is perpendicular to the first, as represented in fig. 11, the vibrations which have passed through the first being now perpendicular to the second, will also now be stopped by the

second plate in such a position, and, as it is turned round, there will be found to be two positions in which the polarized light passes through the analysing plate, and two positions in which it will not pass through, being wholly stopped; these positions being at right angles to each other, as will be understood by fig. 11, where *a a* is the first or polarizing plate, and *b b* the second or analysing plate, overlapping the first.

Having thus briefly considered the phenomena of polarization according to the undulatory theory, we must now, in the same way, notice the explanation which this theory also affords of the splendid phenomena of colours. For this purpose we must first consider the phenomena of interference, which, it will readily be seen, must necessarily result from the mechanical laws of vibratory or undulatory motions, and which have consequently been a principal means of establishing the Huygenian theory, and were first originated and most ably propounded and applied by Dr. T. Young.

Fig. 12

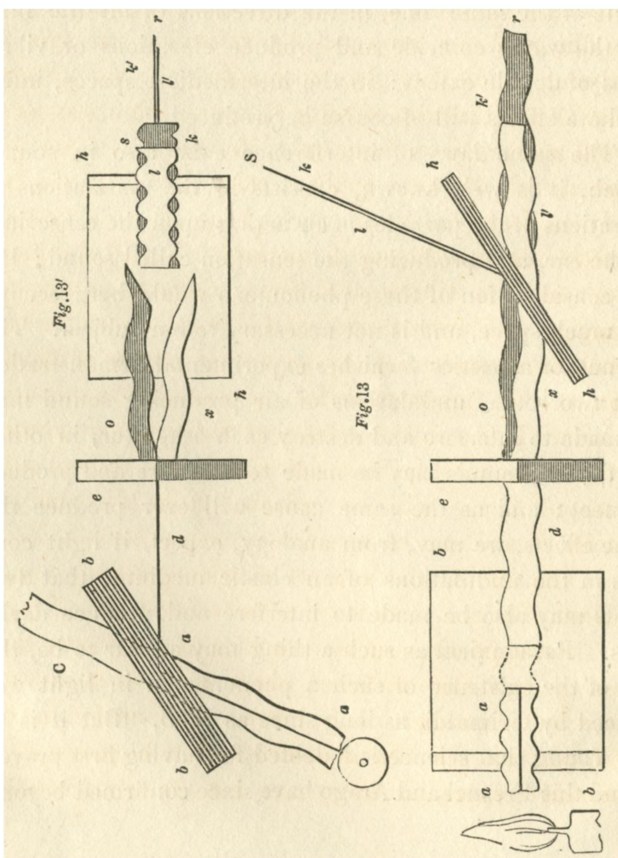


Let fig. 12 represent two sets of waves, propagated on the surface of a still pond of water from two points *a a*, the black lines or circles representing the tops of the waves; it will be seen that, along all the lines *b b*, the waves interfere just half way between each other, so that in all those directions there will be a smooth surface, provided each set of waves is produced by precisely the same degree of disturbing force, so as to be perfectly equal and alike in every respect, and the first wave of one set exactly half a wave in advance of the first wave of the other; while at the same time, in the directions of all the lines *c c*, the waves coincide and produce elevations or vibrations of double extent: in the intermediate spaces, intermediate effects will of course be produced.

The same laws of interference exist also in sound, which, it is well known, consists in the undulations or vibrations of the particles of air acting upon the sensorium of the ear, and producing the sensation called sound; but the consideration of these phenomena would here occupy too much space, and is not necessary to our subject. The science of acoustics furnishes experimental demonstration that two sets of undulations of air producing sound may be made to interfere and destroy each other (or, in other words, two sounds may be made to interfere and produce silence); and as the same cause will ever produce the same effects, we may, from analogy, expect, if light consists in the undulations of an elastic medium, that two lights may also be made to interfere and produce darkness. Paradoxical as such a thing may appear to be, the fact of the existence of such a phenomenon in light was noticed by Grimaldi, as long since as 1665. But it is to Dr. Young that science is indebted for having first proved —and this Fresnel and Arago have since confirmed beyond

all question or dispute—that certain dark bands and coloured fringes are produced by the interference of light.

It is quite impossible, in a paper like this, to do justice to this great and important branch of the theory; and as we are now considering only the phenomena of colours in polarized light, the explanation already given of the interference of the undulations in water, will enable us to understand how the splendid colours are produced, according to the laws of interference, by the action of doubly refracting bodies upon polarized light.



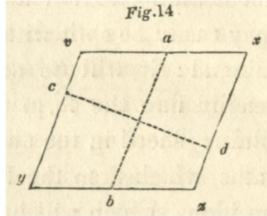
For this purpose let *d*, figs. 13, 13′, be the polarized ray incident perpendicularly upon any double refracting crystal; the best for this purpose will be a thin film of selenite *e*, which is represented edgeways, and should be about the fortieth or fiftieth of an inch in thickness, and may easily be split with a knife from a large piece of the mineral: it will be quite transparent, and break most readily into the form represented by fig. 14. If such a film is placed in the object-holder of the polarizing apparatus attached to the hydro-oxygen microscope in certain positions, which will hereafter be explained, an image of the film will be projected by refraction through the analysing bundle *h* of glass upon a screen in the direction *r*, fig. 13; but instead of being clear and colourless, as the crystal appears in ordinary light, its whole figure will be covered with the most brilliant colours, and, if of a perfectly uniform thickness throughout, it will be of a perfectly uniform colour throughout; but if of different thicknesses, it will be of different colours, varying and changing with every degree of thickness, no matter how minute or imperceptible by any other means of observation, or the most powerful microscopic examination. Polarized light exhibits a different tint for every variation, but all of the most brilliant description. At the same time a second image will be reflected from the analysing bundle *h*, and can be received upon a second screen in the direction *S*, the colours of which will be equally brilliant, but complementary to the other reflected rays.

Thus, supposing we have a film of a uniform thickness, giving in the refracted image *r* a red colour, then the reflected image *s* will be green. The same thing will take place if the film is of different thicknesses giving different colours, as every tint has its complementary

colour, and those of one image will always be complementary to the other; that is, if blended together or superposed, will make white light.

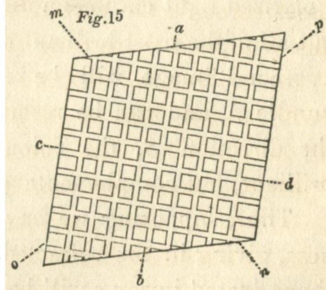
Now, if the film is made to turn round in such a manner that the points or angles *v y z x*, fig. 14, may follow each other and be alternately uppermost, the polarizing and analysing parts of the apparatus remaining stationary, there will be found certain positions in which the film will have no action upon the polarized light *d* passing through it: these positions are when either of the cross lines, *ab* or *cd*, is parallel to the plane in which the vibrations of the polarized ray are supposed to take place, which in *d*, fig. 13, is represented to be in the perpendicular.

Fig.14

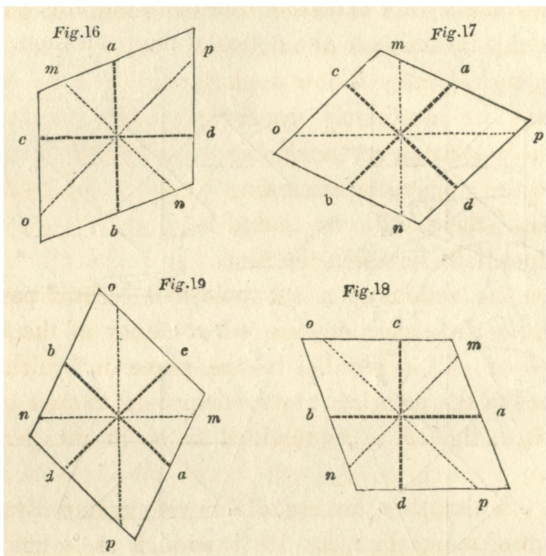


The selenite, then, we see, differs very materially from the plate of tourmaline, fig. 10, inasmuch as it has four positions in which polarized light passes through it without undergoing any change; whereas, in the tourmaline, there are only two such positions. We may suppose, then, the structure of the selenite to be represented by fig. 15, where *ab* is one axis, which, when parallel to the plane of vibration of the polarized light, it will pass through without undergoing any change, as it would through a single plate of tourmaline under similar circumstances, and *cd* the other axis, in which the same thing takes place.

Fig.15



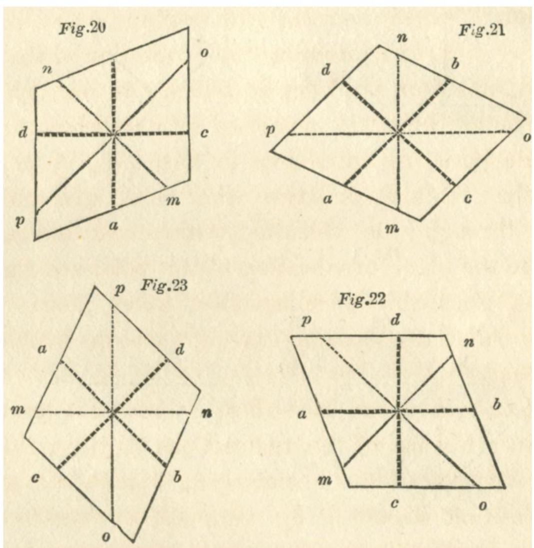
These different positions are shewn in the following figures. In fig. 16 the axis *a b* is parallel to the plane in



which the vibrations of the polarized light *d*, fig. 13, are performed. In such a position, we have shewn, the light passes through the crystal without suffering any change. This is proved by causing the analysing bundle of glass *h h* to revolve, the selenite remaining stationary; when it will be seen that at each quarter of a circle the light will be alternately reflected, and transmitted or refracted in just the same way that it is when the selenite is removed: as we have previously noticed in explaining the action of the analysing bundle of glass.

As the film is turned round, it will be alternately in the positions shewn in figs. 16, 18, 20, 22, where the same thing occurs. Hence these lines in the selenite

a b and *c d* are called neutral axes; because, in the positions described, it exerts no action upon the light passing through it; while, in the intermediate positions,



it does alter the character of the light, and in which all the splendid phenomena of colours are seen.

Let us now suppose the film to be turned from its first position in fig. 16: as soon as it begins to move, the two images seen at *r* and *S*, fig. 13, will begin to exhibit the most brilliant colours, which will increase in brightness until the film reaches the position shewn in fig. 17, where they will be at their maximum or greatest brilliancy; and when *r* is red, *S* will be green; or if *r* is blue, *S* will be orange, &c. &c. But, as the film turns, the colours will fade; till, having reached the position shewn in fig. 18, where they will be at their minimum

or nothing, there being no action exerted by the film in such a position; but, as soon as it has passed by, the colours begin again to return, till it has reached the position shewn in fig. 19 where they are again at their maximum. The same thing will occur at every quarter of a circle; and, in continuing the revolution of the film, we shall find four positions in which the film exerts a peculiar action upon the polarized light passing through it. These positions are shewn in figs. 17, 19, 21, and 23, so that we also find two other lines, *m n* and *o p*, passing through the selenite, which are alternately parallel to the plane of vibration of the polarized light *d*, fig. 13. When this peculiar effect takes place, these lines are called depolarizing axes, for reasons which will soon appear.

Now, to understand how these colours are produced by the interference of the undulations of the light, let the film *e* be placed in the polarizing apparatus, fig. 13, in the position shewn in fig. 17, with the two neutral axes *a b* and *c d* inclined 45° on each side of the plane of vibrations of the polarized light, or perpendicular, and of such a thickness as to give a red image at *r*, and a green one at *S*, fig. 13. If the analysing bundle *h h* is now removed, the image will still be seen at *r*, but perfectly clear, not having the least appearance of colour. It is evident, then, that the analysing part of the apparatus is equally necessary for the production of colours. Let us, however, first notice what the action of the selenite *e*, fig. 13, is in such a position upon the polarized light passing through it. Now, being a doubly refracting crystal, when its neutral axes *a b c d* are thus inclined, the light passing through it will be doubly refracted; and, although not perceptible to the eye by ordinary

observation from the extreme minuteness of the separation in so thin a film, yet, from this property which we know it possesses, it is nevertheless divided into two equal portions or sets of waves, the vibrations of one being parallel to the neutral axis *a b*, and the vibrations of the other parallel to the axis *c d*, and, consequently, both inclined 45° to the perpendicular, as shewn at *o x*, fig. 13 : *o*, we may call the ordinary ray, and *x* the extraordinary ray.

But in the passage of the two rays through the crystal, they have traversed it in different directions, with different velocities: one of these sets of waves will, therefore, on emergency, be retarded and lie behind the other; but, being polarized in different places, cannot interfere. To cause them to interfere and exhibit the phenomena of colours, their planes of polarization or vibration must be made to coincide. For this purpose, let the analysing bundle of glass be placed as at *h h*, in which position the vibrations of both the ordinary and extraordinary rays *o* and *x* are each inclined 45° to a plane perpendicular to the plane of reflection, and, consequently, as we have shewn at page 44, that vibrations in a beam of ordinary light, inclined at angles between the perpendicular and horizontal planes, are divided into two portions, one of which is reflected, and the other transmitted or refracted; so now again, the same effect will of course take place, and the vibrations or waves of the reflected half *k* of the ordinary ray *o*, will be in a plane parallel to the plane of reflection of *h h*, and the waves of the reflected half *l* of the extraordinary ray *x*, will also be in the same plane. Here, then, we have two sets of waves originating from the same vibrations in the polarized ray *d* brought into the same plane, and, consequently, now possessing all the conditions necessary for

interfering with each other; and the same also in the two transmitted portions, the half k' of the ordinary ray o, and the half l' of the extraordinary ray x, in both of which the waves are in a plane perpendicular to the plane of reflection.

The colours of the images at r and S produced by this interference will depend upon the interval of retardation of one of the rays within the medium e, which, of course, will vary with its thickness.* When this thickness is such as to cause the interval of retardation to amount to half a wave in the reflected rays k and l, they will interfere half way between each other, and so far destroy each other as to produce in the image at r the black of the first order, seen by reflection, in Newton's "Table of Colours;" while, in the transmitted rays k' and l', the waves being in opposite phases of vibration, will coincide and exhibit in the image S, the white of the same order seen by transmission. When the thickness is such as to cause an interference in intermediate degrees, intermediate effects or colours will be produced; consequently, when there is exhibited at r any one of the colours in Newton's Table seen by reflection, the image at S will always exhibit the complementary colour seen by transmission, the waves of one being always in opposite phases of vibration to the waves of the other.

And we shall find, as the film of selenite is made to revolve, the bundle $h\,h$ remaining stationary, that it will produce one colour only at r, which will be seen in

* The different colours being produced by waves of different lengths, the amount of retardation will be different with each; consequently, the thickness of medium that will act with full effect on the waves of one colour will be either too thick or too thin to have the same effect on the waves of the other colours.

the four positions shewn at figs. 17, 19, 21, and 23, appearing and disappearing alternately as it passes through them, and the same with the complementary colour at *S*. But if the film is fixed in any of the positions in which it gives the brightest colour, and the bundle of glass *h h*, fig. 13, made to revolve, two colours will be seen both at *r* and *S*, which change alternately at each quarter of a circle; thus, when *h h* is in the position shewn at fig. 5, and the image at *r*, fig. 13, is red, and *S* green; when *h h* has turned round 90°, *r* will be green and *S* red; at 180° *r* will be again red and *S* green, and at 270° *r* will be again green and *S* red.

These, and all the splendid phenomena of colours in polarized light, will readily be seen to be simple consequences resulting from transversal vibrations; for, when a single wave or vibration in any one plane, as at *d*, is divided or resolved into two at right angles to each other, one will of necessity be half a wave behind the other, the two being the opposite halves of the same in *d;* and as each of these, *o* and *x*, is again divided or resolved into two others, there will be four waves or vibrations produced from the original one. Two of them in one plane must of necessity coincide or conspire, while the two in the other plane are opposed.

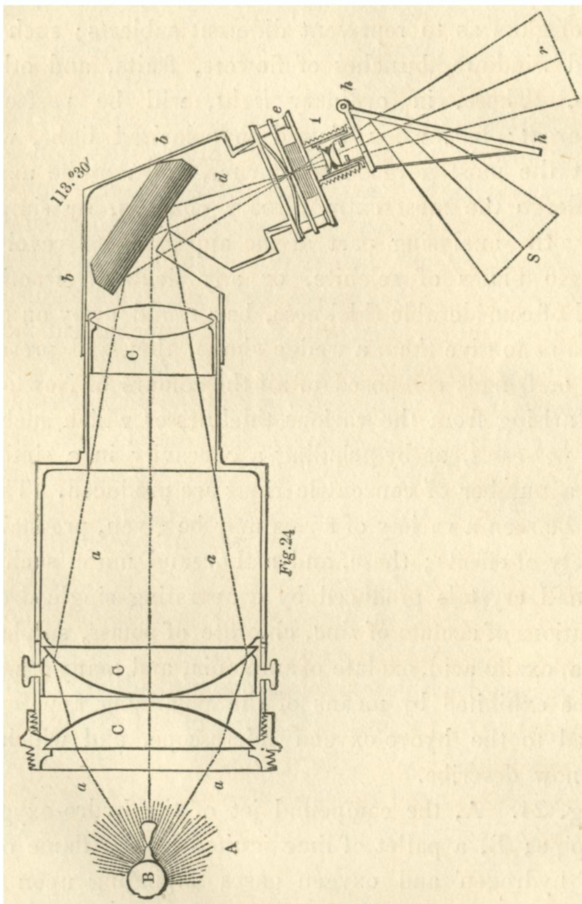
The colours produced by the interference in one plane have been shewn by Fresnel to correspond to the amount of retardation within the crystal, and that in the other plane to be due to the same amount of retardation augmented or diminished by half a wave, and consequently complementary to the former.

In this brief notice of polarized light, I have confined my explanation to the phenomena exhibited by a single plate or film of selenite; the colours of which we have

seen, vary with its thickness. With this single crystal, then, numerous splendid and beautiful effects may be produced, simply by procuring different thicknesses for giving different colours, and so arranging them upon a plate of glass as to represent different subjects; such as painted windows, bunches of flowers, fruits, and other figures. These, in ordinary light, will be perfectly transparent; but, when viewed in polarized light, will exhibit the most gorgeous colouring, and may be made to undergo the most extraordinary changes, by simply causing the analysing part of the apparatus to revolve. If single plates of selenite, or any doubly refracting crystal of considerable thickness, be ground away on one edge so as to give them a wedge shape, they will present bands or fringes composed of all the colours of Newton's Table arising from the various thicknesses which such a shape possesses, or by grinding a concavity in a similar plate, a number of concentric rings are produced. Thus it will be seen a variety of forms may be given, producing a variety of effects; these, and a thousand more, such as the small crystals produced by evaporating single drops of solutions of acetate of zinc, chlorate of potass, sulphate of soda, oxalic acid, oxalate of ammonia, and many others, may be exhibited by means of the polarizing apparatus adapted to the hydro-oxygen microscope, and which I shall now describe.

Fig. 24. A, the compound jet of the hydro-oxygen blow-pipe; B, a pallet of lime ignited by the flame of a jet of hydrogen and oxygen gases impinging upon it; *a*, diverging rays of light refracted by the condensing lenses C C C, and falling upon a mirror *b b*, composed of ten plates of thin flatted crown glass, placed in the elbow of a tube bent to the polarizing angle of crown glass.

d, conveying rays of polarized light reflected from the mirror; *h h,* a bundle of sixteen plates of mica for analysing the light previously polarized by reflection; *e,* a



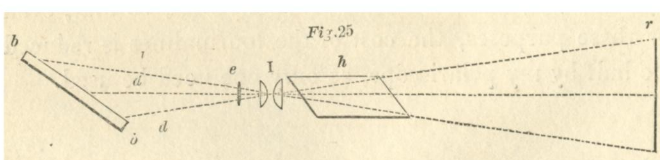
double reflecting crystal (film of selenite) placed in the focus of the object-glass I, which forms an image of the crystal upon a disc or screen at *r.* As the analysing

bundle of mica *h h*, is made to revolve (or turn round), the image of the selenite upon the disc undergoes all the changes, and exhibits alternately the primary and complementary colours. This apparatus has the advantage of exhibiting both the primary and complementary colours at the same time, one being reflected in the direction *S*, and the other transmitted and seen at *r*.

The great advantage of polarizing the light by reflection from a number of plates, is the obtaining a beam of any required dimensions, of much greater intensity than by any other means; for, whatever single surface may be employed that polarizes the light at the same angle as the glass used (which, for crown glass, is 56° 45′), we obtain an additional quantity by laying on it a single plate of such glass, and a further quantity by the addition of a second, third, or any further number; the quantity of light added by each succeeding plate being, however, less in proportion to the number of plates through which it has previously to pass.

In this respect, the single image (Nicols's) prism of Iceland spar is decidedly the best for analysing, as by this a great variety of objects may be exhibited. Its application is shewn in fig. 25, where *e* is the selenite placed

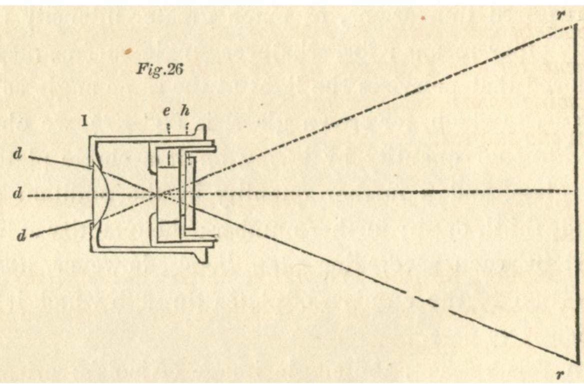
Fig. 25



in the rays *d d d* of polarized light, an image of which is projected by the lenses I. *h* is the analysing prism through which the rays of light *r r* are refracted.

But there is one class of phenomena, viz. the rings seen to encircle the optic axes of crystals, the number of which increase in some crystals (the topaz, for example), with the divergence of the rays of polarized light passing through them. It will be evident, then, that the tourmalines enable us to exhibit more of these rings, and upon a larger scale than the prism, which will be better understood by the arrangement shewn in fig. 26. *d d d*,

Fig. 26



converging rays of light polarizing by reflection; I, a lens of short focus transmitting a cone of light, with an angle of divergence for its rays *r r*, of 45°. *e*, a crystal, say topaz; *h*, the tourmaline for analysing; so that, even for these purposes, the cost of the tourmalines is reduced one half by my polariscope, as only one need be used.